

# Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718

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## Introduction

*“NASA is currently constructing what will be the most powerful rocket ever built, the Space Launch System, or SLS. Its initial 70-metric-ton configuration will stand taller than the Empire State Building, provide 10 percent more thrust than the moon-trekking Saturn V and carry three times the payload of the space shuttle.*

*But not only is NASA aiming to take us yet again where no person has gone before, it’s also aiming to do that through the most efficient, cost- effective means possible. Toward that end, the agency is looking to break the mold of conventional rocket engine fabrication by introducing additive manufacturing — popularly known as 3D printing — to the process.”*

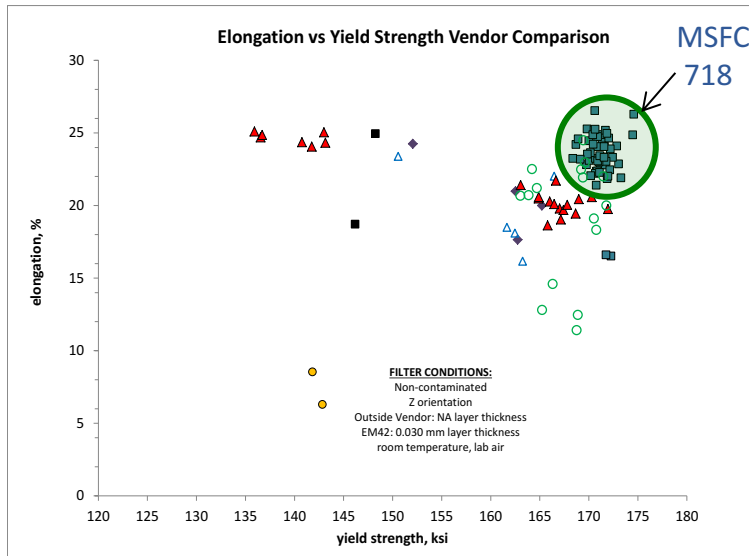
*~NASA Technology & Innovation; V17.01*

## Agenda

- Why We care about Defects in additive materials.
- Example of defects we’ve encountered in our development.
- Effect of defects on mechanical properties.
- Conclusions

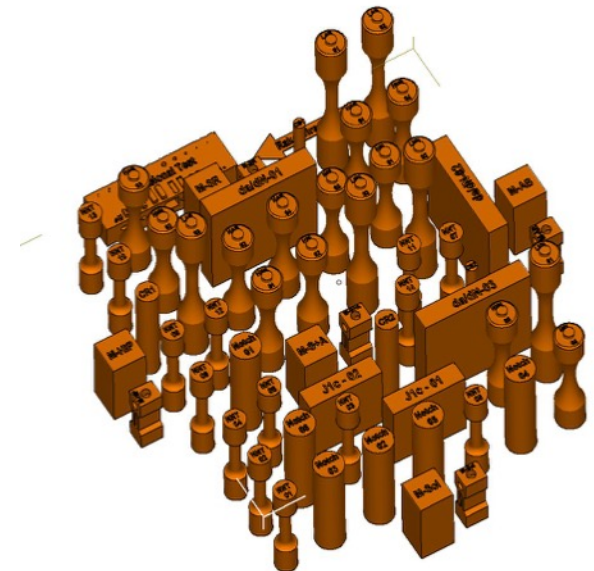
Why do we care about defects?

# AM Inconel 718 Round Robin



- Early comparisons of IN718 produced by MSFC and by vendors indicated significant variations in mechanical and microstructural properties, which raised concerns about certification of parts produced via AM.
- Participants used a variety of OEMs and machine models, providing a diverse array of SLM build parameters.
- The vendors were provided build files, instructions for metallography specimens, and heat treatment specifications but otherwise allowed to use in house processes.

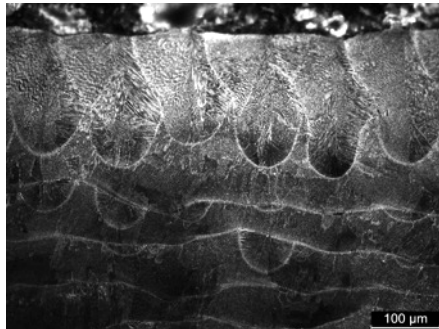
LAB	OEM	Model	Power (W)	Speed (mm/s)	Hatch (mm)	Layer Thickness (micron)	Rotation Angle
MSFC	CL	M1	180	600	.105	30	90
LAB A	EOS	-	-	-	-	40	-
LAB B	EOS	M270	195	-	-	40	67
LAB C	EOS	M280	305	1010	.110	40	67
Lab D	EOS	M280	285	960	N/A	40	67



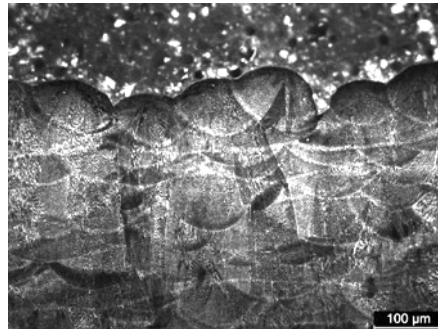
# Round Robin: Microstructure

- As-built microstructures are dominated by the characteristics of the melt pool, which vary based on build parameters.
- Following heat treatment, the microstructure recrystallizes and resembles the wrought microstructure, with some expected grain size variation. IN718 derives strength properties from precipitates in the nickel matrix, which are produced during the solution and aging heat treatments.

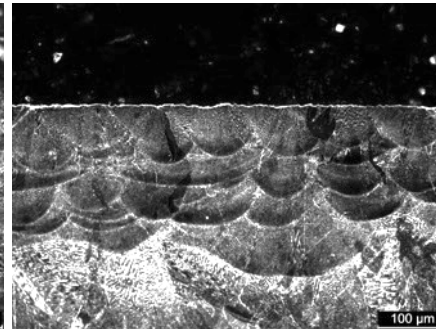
MSFC M1



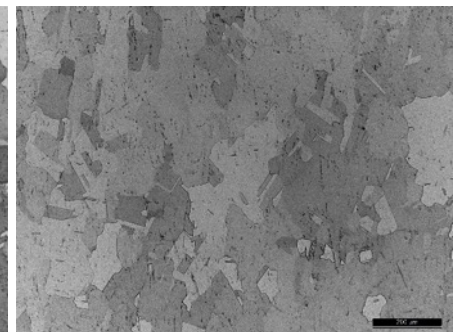
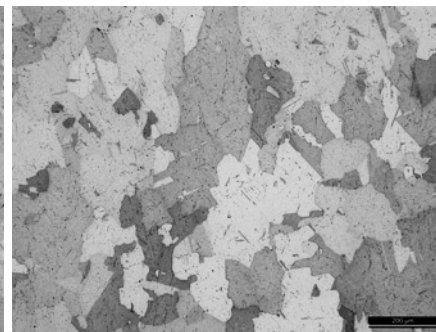
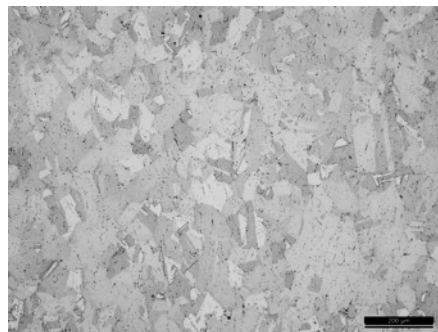
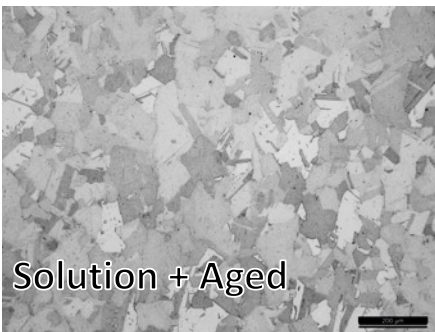
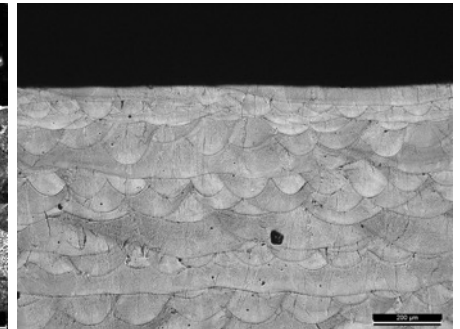
LAB B M270



LAB C M280

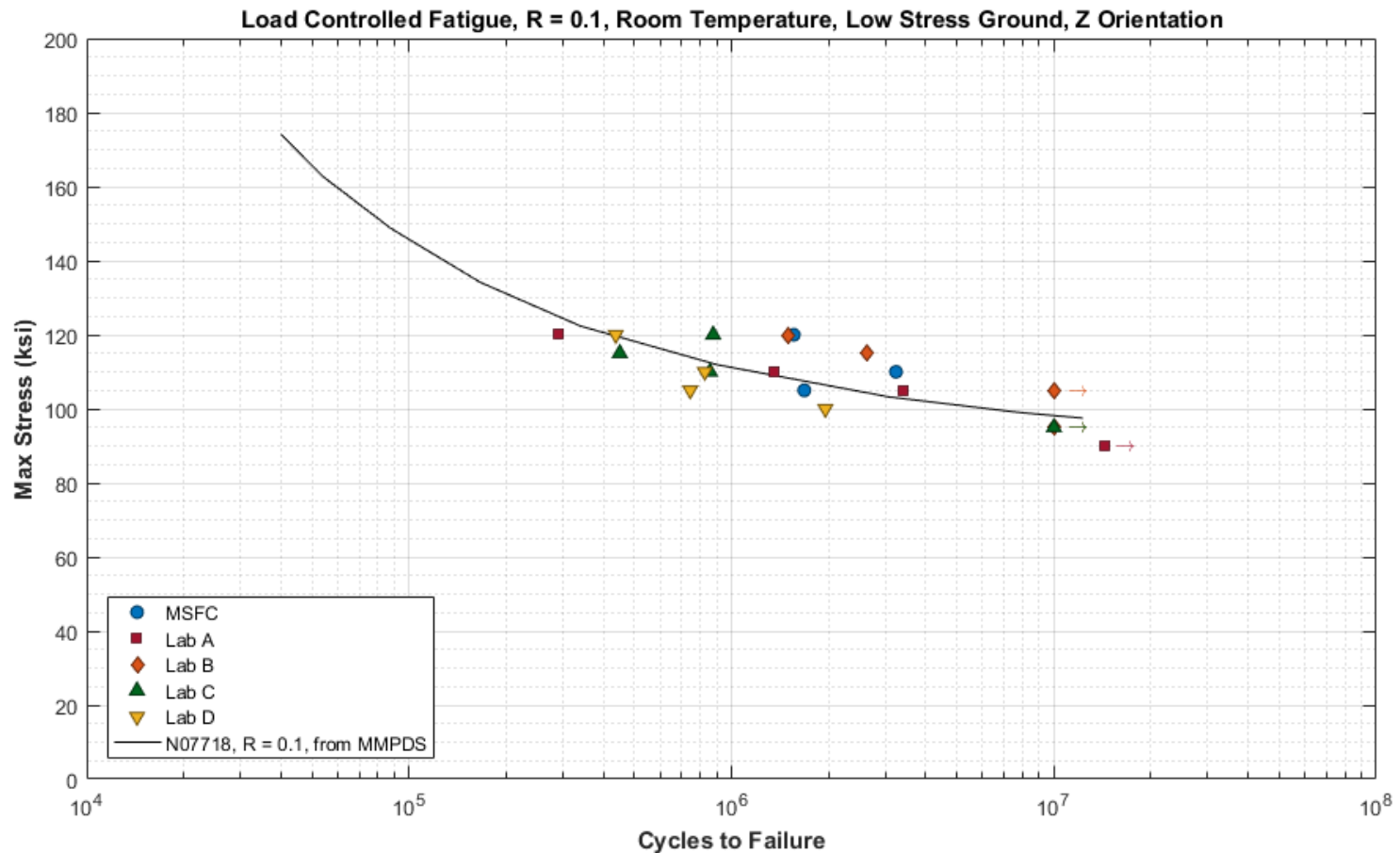


LAB D M280



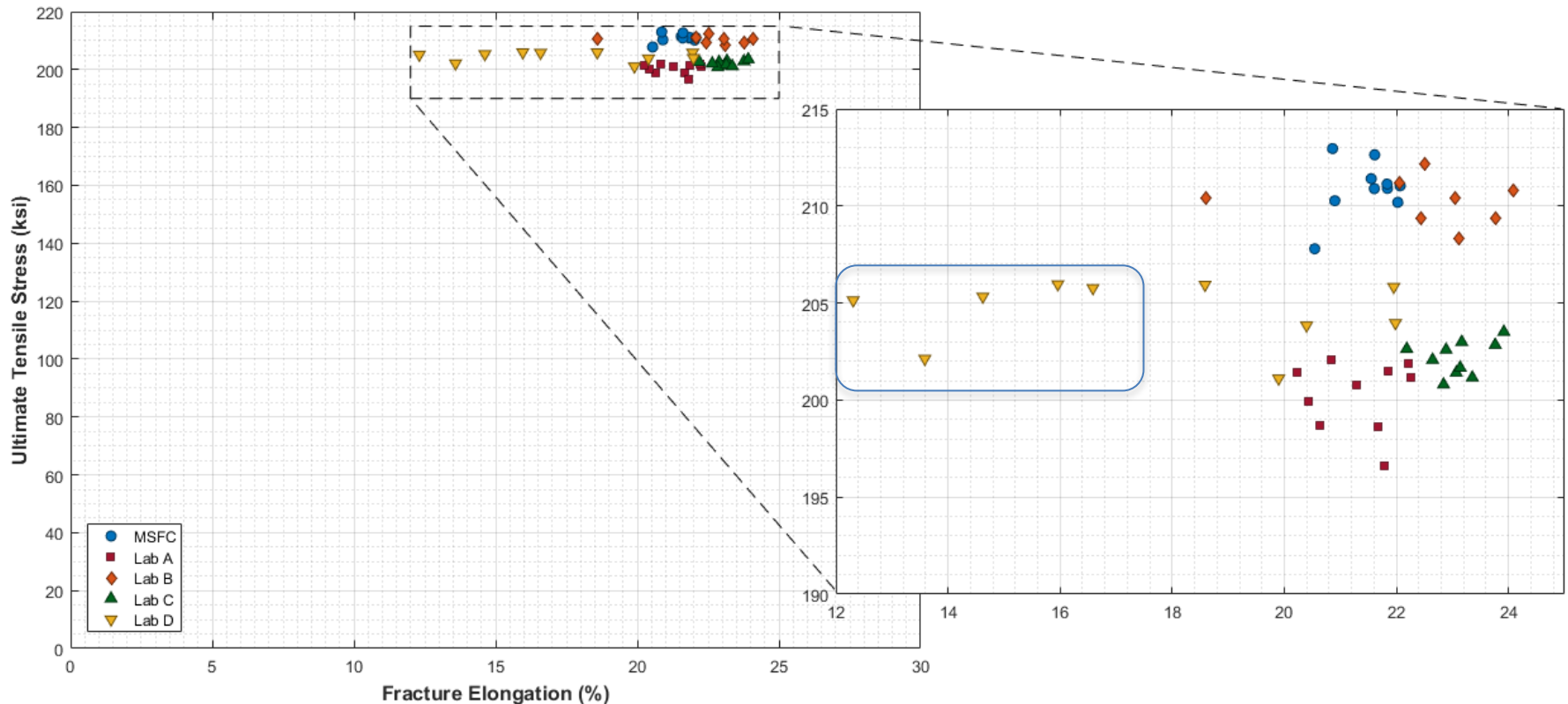
# Round Robin: High Cycle Fatigue

- High cycle fatigue tests align well with an IN718 fatigue reference curve from MMPDS.
- Cycles to failure at a particular stress trended along with ultimate tensile strength, as expected.



# Round Robin: Tensile Properties

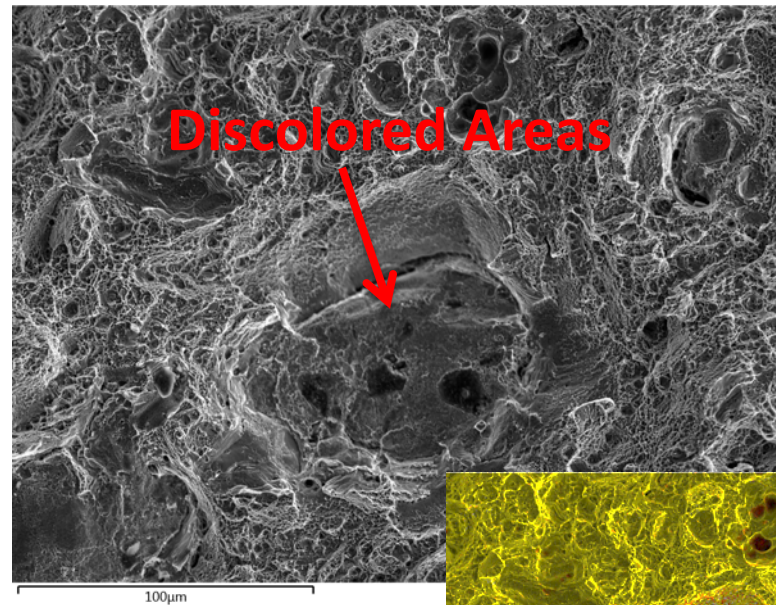
- At room temperature, most builds exhibited tightly grouped results, with the exception of Lab D, which has considerable variability in ductility (fracture elongation).
- From past experience, lower elongation is an indication that defects were present in the material.



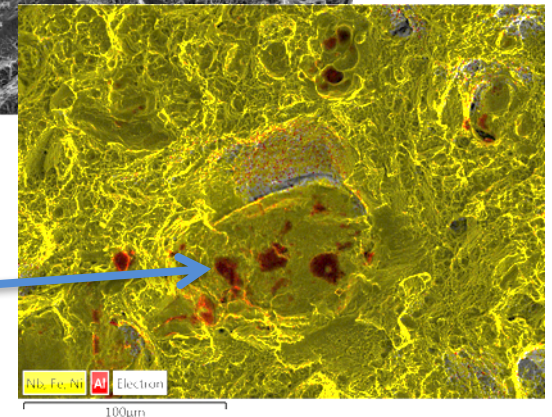


# Round Robin: Fractography

- Optical examination of the fracture surfaces of Lab D specimens show numerous discolored on the fracture surfaces.
- EDS mapping of these areas show that these areas are oxidized.
- It is clear that the elongation results from Lab D underperformed due to lack of fusion defects.



EDS show  
presence of  
Aluminum Oxide



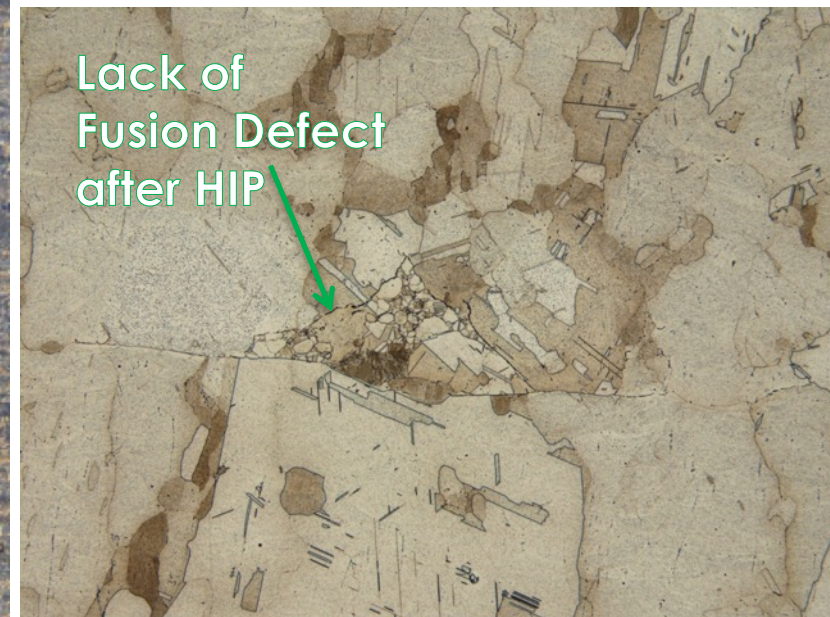
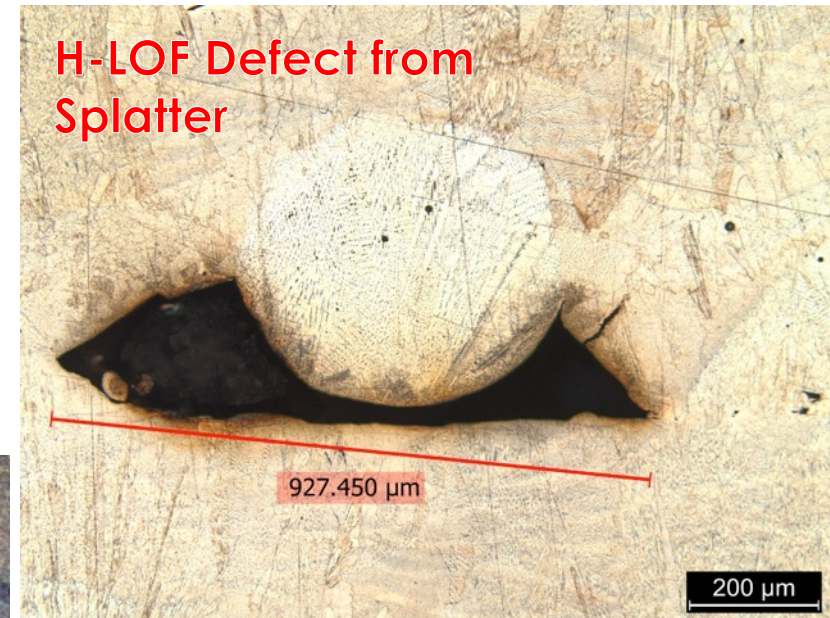


# Defect Examples

# Lack of Fusion Defects

## Horizontal Lack of Fusion Defects

- Horizontal Lack of Fusion Defects are generated in several ways:
  - Low power/high speed settings.
  - An attenuated laser.
  - Splatter falling on surface.
- This type of defect is considered detrimental to mechanical properties.



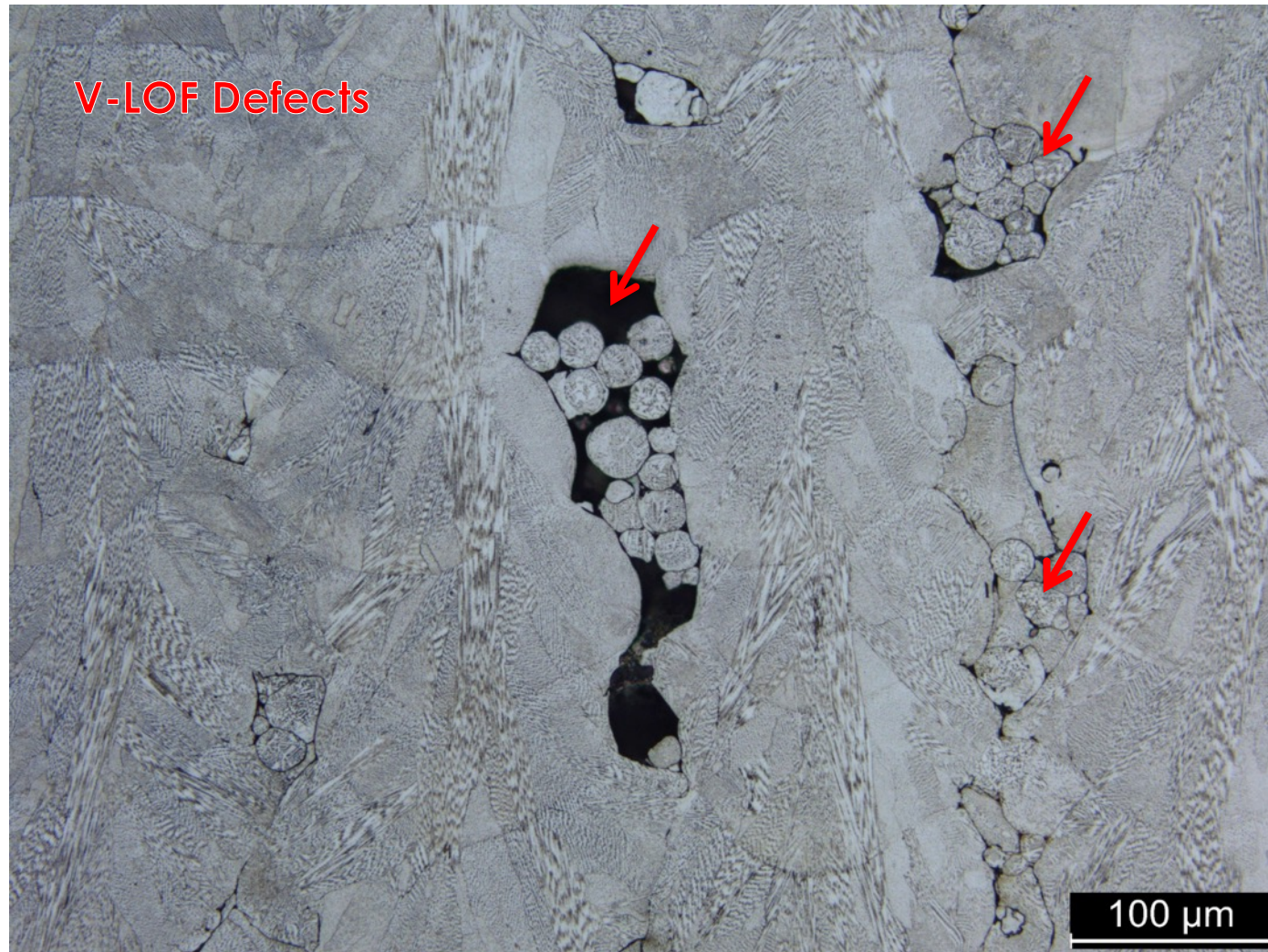
**H-LOF Defect from Laser Attenuation or Low Energy Density**



# Lack of Fusion Defects

## Horizontal Lack of Fusion Defects

- Vertical Lack of Fusion Defects occur when the hatch spacing parameter is too wide.



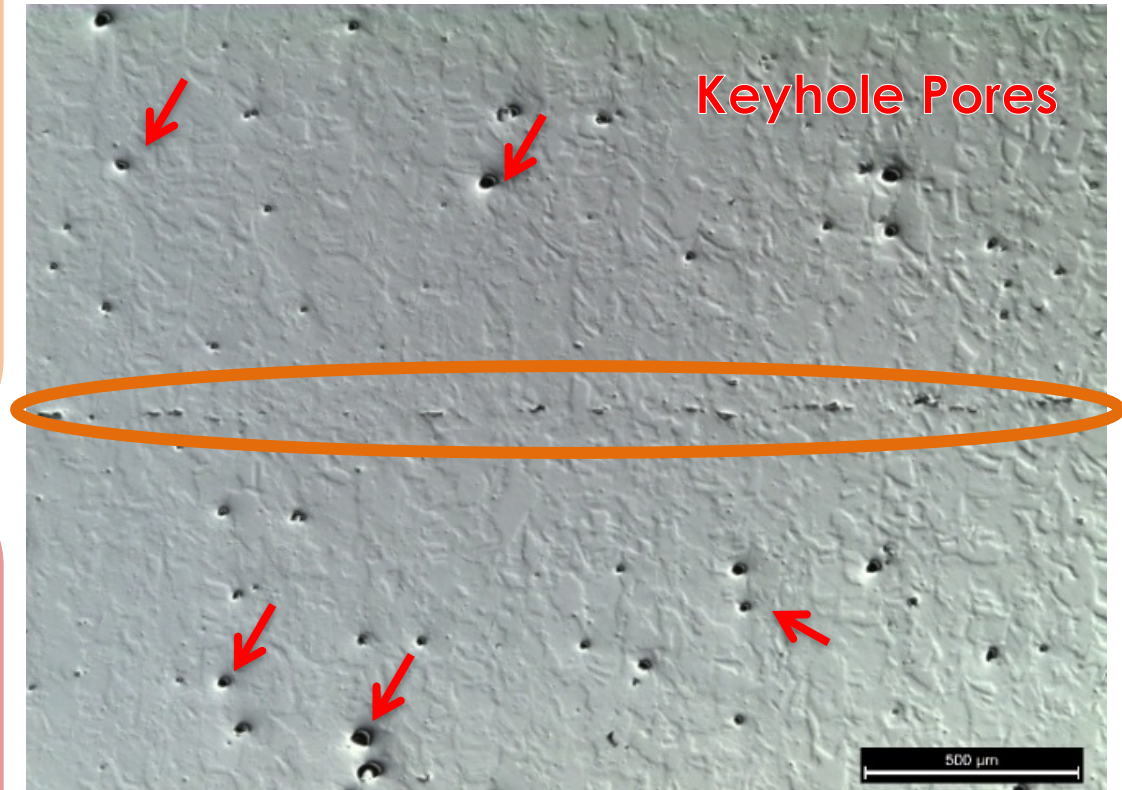
# Lack of Fusion Defects

## Short Feed (Skipped Layer) and Spherical Porosity

Short Feed Defect occur when there is not a sufficient amount of powder to cover the powder bed.

When enough powder is eventually supplied some number of layers later, the layer is too thick for the laser to penetrate completely.

Spherical porosity occurs when the energy density of the laser is high enough to generate a “keyhole” melt pools. Although we develop parameters to achieve 100% density, this porosity generally “heals” in the HIP and we do not have data on their effect on mechanical properties.

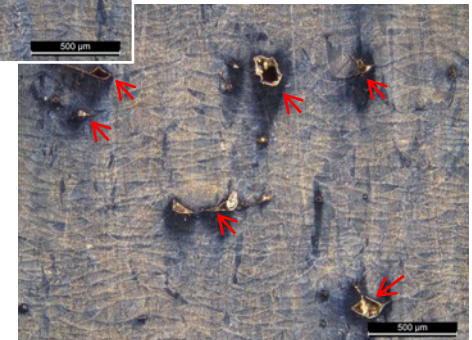
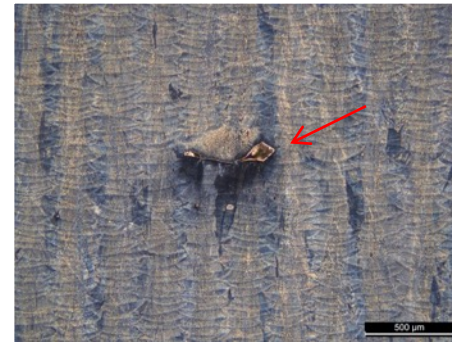
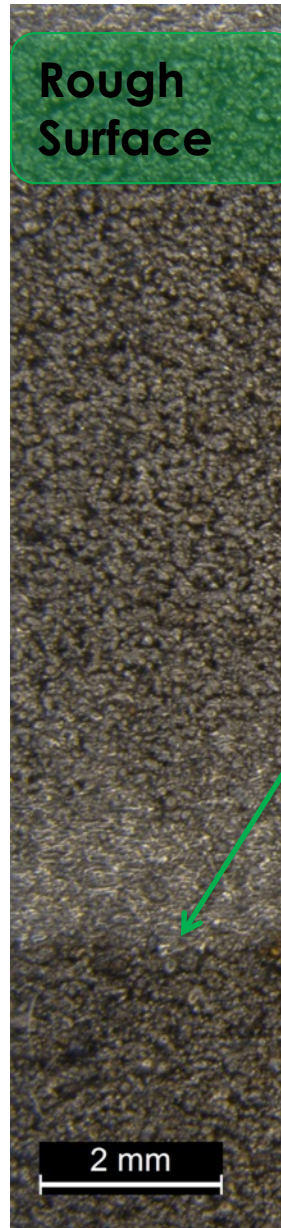




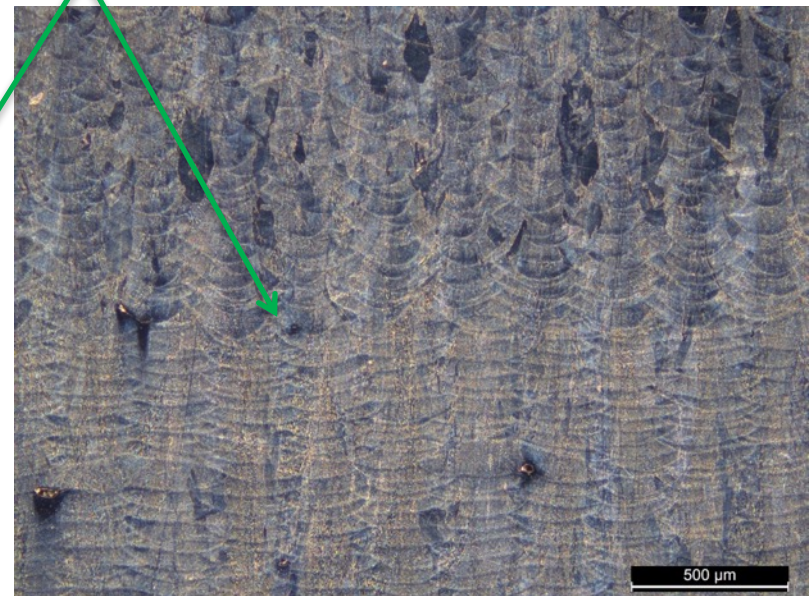
# Surface Defects

## Rough Surface From Attenuated laser

- During a build with a large of cross sectional areas, discoloration of the top surface was observed.
- This discoloration went away when the lens was cleaned during a build stoppage.
- Upon completion, it was observed that there was a gradual degradation of the surface roughness that also went away when the lens was cleaned.
- Subsequent microscopy of the specimens from this build revealed that the areas where the surface was rough contained lack of fusion defects and generally displayed shallow melt pools.
- It was clear that soot and fine particulate ejected from the build process was being deposited on the lens.
- This attenuated the laser—effectively reducing the power density.



**Lens  
Cleaning**

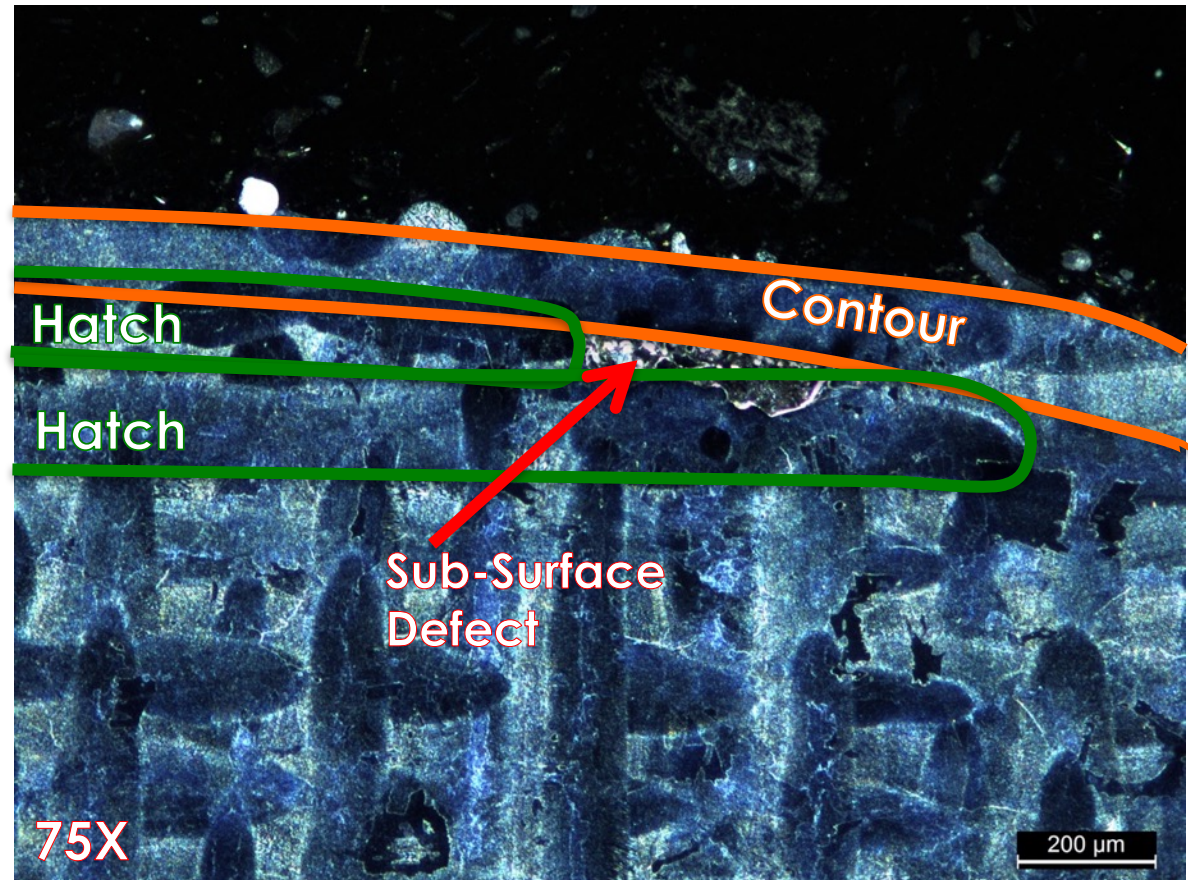




# Surface Defects

## Sub-Surface Defects

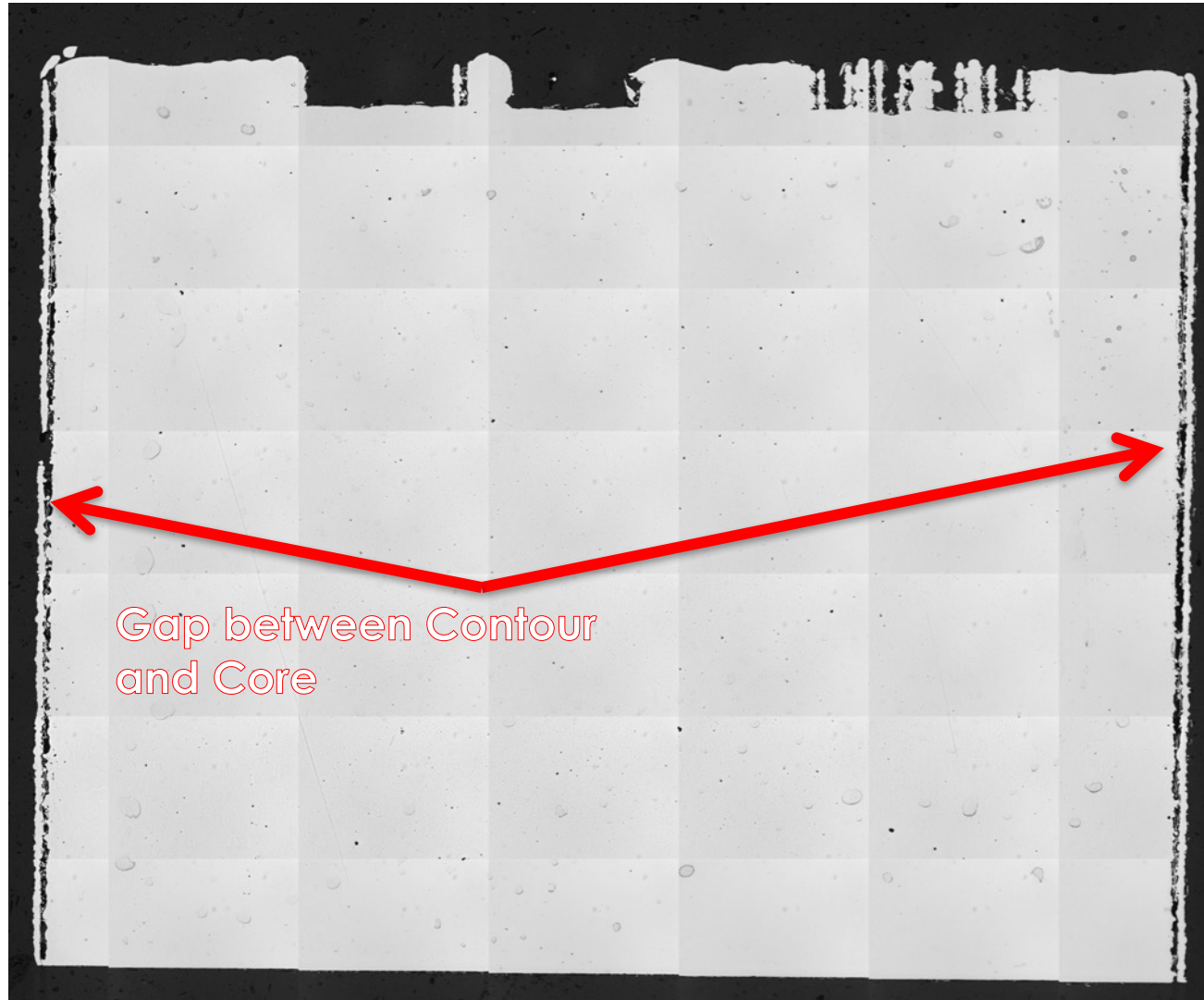
- Sub-Surface defects are created when the offset is too large.
- These defect will not "heal" during the HIP Process.
- During HT the free surfaces of these defects will oxidize.
- This creates fatigue initiation sites that reduce HCF life.



# Surface Defects

## Detached Contour

- Detached Contours occur when the offset is too large.
- These usually result in parts with superior surface finish, but the defect is undesirable for obvious reasons.

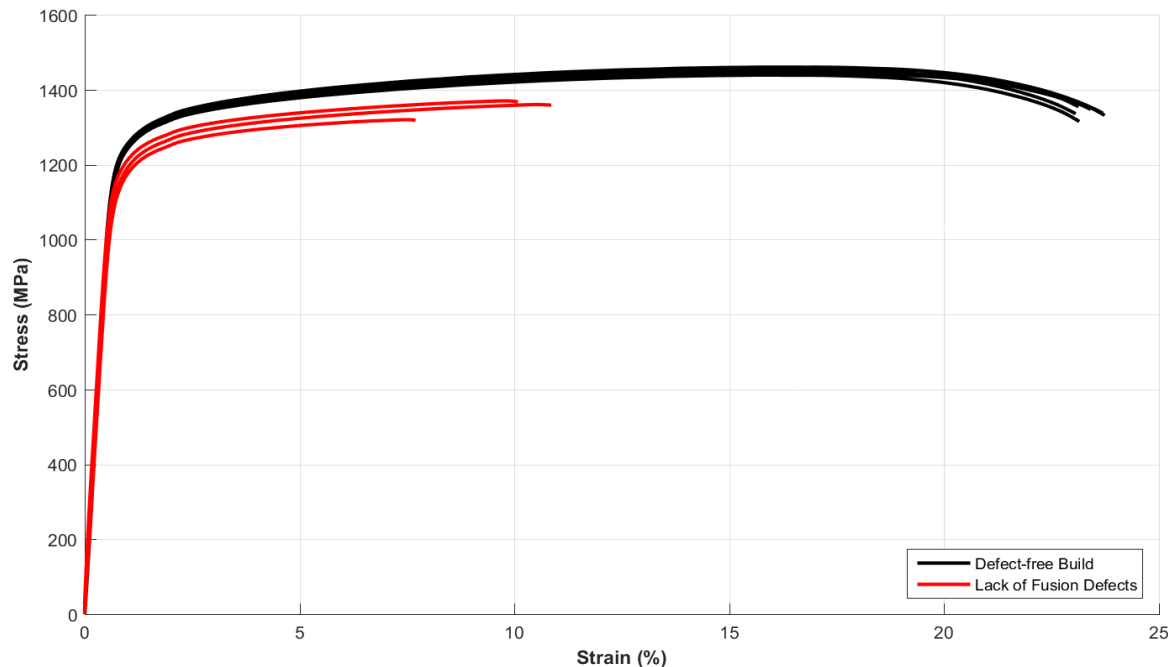


# Defect Consequences and Classification

# Effect of Defects on Mechanical Properties

## Horizontal Lack of Fusion

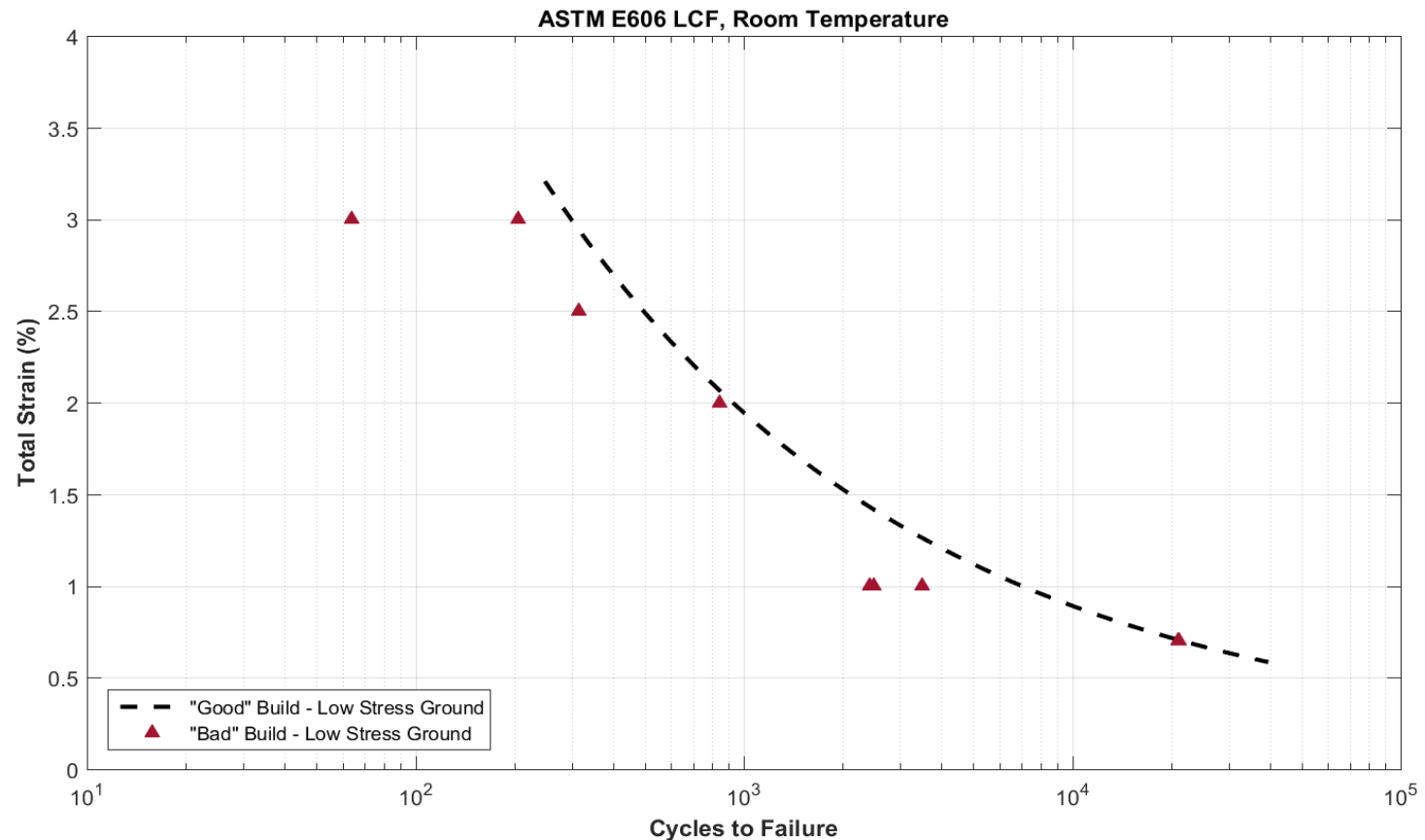
- H-LOF defects result lower than expected tensile properties.
- There is a noted drop in the elongation of material with these defects.



# Effect of Defects on Mechanical Properties

## Horizontal Lack of Fusion

- H-L0F defects also reduce Low-Cycle Fatigue Life.





# Defect Classification

- **Bulk Defects**

- **Lack of Fusion**
  - **Horizontal Lack of Fusion Defect**
    - Insufficient Power
    - Laser Attenuation
    - Splatter
  - **Vertical Lack of Fusion Defect**
    - Large Hatch Spacing
  - Short Feed
- **Spherical Porosity**
  - Keyhole
- **Welding Defects**
  - Cracking

- **Surface Defects**

- **Worm Track**
  - High Energy Core Parameters
  - Re-coater Blade interactions
- **Core Bleed Through**
  - Small Core Offset
  - Overhanging Surface
- **Rough Surface**
  - Laser Attenuation
  - Overhanging Surfaces
- **Skin Separation**
  - Sub-Surface Defects
  - Detached Skin

For the purpose of this presentation a defect is defined as a deviation from nominal. Although some of them are tolerable, many of these defects will result in the degradation of mechanical properties or cause the part to be out of tolerance. The majority of them; however, can be mitigated through parameter development and process controls. The List to the right is color coded to show the known causes of the defects.

- **Parameters**
- **In-Process Anomaly**
- **Material Property**

# Defect Consequences

- **Bulk Defects**

- **Lack of Fusion**
  - **Horizontal Lack of Fusion Defect**
    - Insufficient Power
    - Laser Attenuation
    - Splatter
  - **Vertical Lack of Fusion Defect**
    - Large Hatch Spacing
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- **Spherical Porosity**
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- **Welding Defects**
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- **Surface Defects**

- **Worm Track**
  - High Energy Core Parameters
  - Re-coater Blade interactions
- **Core Bleed Through**
  - Small Core Offset
  - Overhanging Surface
- **Rough Surface**
  - Laser Attenuation
  - Overhanging Surfaces
- **Contour Separation**
  - Sub-Surface Defects
  - Detached Skin

- The list to the right is color coded to show the effect of the defect on the performance of the part.
- There are some cases where defects were traded against each other. For example, reducing the offset to eliminate the contour separation defects results in the hatch from the core bleeding through the contour. As a result the part will not look as smooth but will perform better.

- **Degradation of Mechanical Properties**
- **Minor or No Observed effect on performance**
- **Out of Tolerance**
- **Unknown**

Conclusions

# Conclusions and Defect Mitigation

## **Conclusions**

- Defects in AM parts can have a substantial effect on mechanical properties specifically tensile elongation.
- The vast majority of defects can be eliminated with careful parameter development.
- Lack of fusion defects caused by machine anomalies are concerning because of their randomness and low detectability.

## **Mitigation for Machine Anomalies**

- Machine Maintenance
- Process Controls:
  - NDE, Witness Specimens, Machine Configuration Control.
  - Perform metallography on development parts to fine tune process. Then limit changes.
- In-Situ Monitoring: This technology is currently not ready to be deployed; however, it will give us the best chance of finding defects in parts.

Backup



# Effect of Parameters on Development Goals

		Elimination of Defects		Microstructure & Mechanical Properties		Build Integrity		Build Time
Core Parameters	Power	<ul style="list-style-type: none"><li>Horizontal LOF</li><li>Splatter</li><li>Welding Defects</li><li>Porosity</li></ul>	Vertical LOF	Grain Size	<ul style="list-style-type: none"><li>Reduction of Columnar Grains</li><li>Grain Competition</li></ul>	<ul style="list-style-type: none"><li>Roughness of Unsupported surface</li><li>Fine Detail</li><li>Up-Skin Smoothness</li></ul>		
	Speed							
	Hatch							
Contour Parameters	Power	<ul style="list-style-type: none"><li>Worm Tracks</li><li>Spikes</li></ul>		<ul style="list-style-type: none"><li>As-Built Surface</li><li>High Cycle Fatigue</li><li>Sub-Surface Oxidation (after HT)</li></ul>	<ul style="list-style-type: none"><li>Surface Finish</li><li>Build Tolerances</li></ul>	Sintered Powder	Reduction of Post Processing	
	Speed					Overhang		
	Offset	<ul style="list-style-type: none"><li>De-bonded Skin</li><li>Subsurface LOF</li></ul>				Core Effect		
Support Strategy						<ul style="list-style-type: none"><li>Overhanging structures</li><li>Easy Removal of Parts from Plate</li></ul>	Reduction of Post Processing Time	

# SLM Process → Structure → Property Relationship

- The variability of materials properties in additively manufactured Inconel 718 can be reduced with a sufficient understand of the Process → Structure → Property relationship.

